

Dark matter subhalos as *Fermi* gamma-ray sources and first candidates in the 1FGL catalog

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Predicted by hierarchical structure formation, Milky Way-type galaxies are anticipated to host numerous dark matter subhalos with masses between 10^{10} and a cut-off of $10^{-6} M_{\odot}$, or even less. In self-annihilating dark matter scenarios, these objects could be visible in the γ -ray band as faint and non-variable sources without astrophysical counterpart. In accordance with realistic subhalo models and current observational constraints on self-annihilating dark matter, we predict that about one massive Galactic subhalo may have already been detected in the 11-months catalog of *Fermi*-LAT data (1FGL). Selection cuts applied to the 1FGL reveal twelve possible candidates, and in-depth studies of the most promising object, 1FGL J0030.7+0724, are presented. In a dedicated X-ray follow-up observation with the Swift XRT, seven point-like X-ray sources have been discovered. Within the positional uncertainty derived from the 24-months *Fermi*-LAT data, we consider the unidentified radio source NVSS J003119+072456, coinciding with one of the discovered Swift sources, as the most promising counterpart candidate for 1FGL J0030.7+0724. The broad-band spectral energy distribution is consistent with a high-energy-peaked blazar. However, flux and extent of the *Fermi* source may also be compatible with a dark matter subhalo. A discrimination between the two scenarios requires further multi-wavelength observations. Strategies for identifying γ -ray sources associated with self-annihilating DM subhalos are discussed.

1. Introduction

Unraveling the nature of dark matter (DM) is part of the major tasks in modern astro- and particle physics. Various independent astrophysical observations indicate a non-baryonic form of cold dark matter (CDM) to prevail over the baryonic content of the Universe, e.g., [1, 2]. Provided by theories extending the standard model of particle physics (SM), such as supersymmetry and universal extradimensions, a class of promising CDM candidates are stable weakly interacting massive particles (WIMPs). By self-annihilation in SM final states (heavy quarks, gauge bosons, or leptons), WIMPs can produce detectable signatures such as photons, antimatter, and leptons, arising from hadronisation and subsequent decay of the final annihilation states. Apart from (loop-suppressed) line contributions, these processes result in continuous photon spectra, following a hard power law (index $\Gamma \lesssim 1.5$) cutting off exponentially to the WIMP mass.

Within the framework of hierarchical structure formation, DM halos of Milky Way-type galaxies should contain numerous DM subhalos orbiting around the center, with masses between a cut-off scale $10^{-11} - 10^{-3}$ and $10^{10} M_{\odot}$ [3], where M_{\odot} denotes the solar mass unit. Within the resolved mass scales, numerical high resolution N -body simulations of structure formation, such as the Aquarius Project [4] or the Via Lactea II simulation [5], predict the subhalos to follow a power-law distribution in mass, $dN/dM \propto M^{-\alpha}$, where $\alpha \in [1.9; 2.0]$; their density profiles resemble the host halo's, resulting in high central densities. Spatially, subhalos follow an “anti-biased” distribution,

i.e., the majority orbits far away from the host's center.

With lacking baryonic but dominating WIMP content, subhalos could appear as non-variable, faint point-like or moderately extended high-energy (HE) γ -ray sources without astrophysical counterpart in any other wavelength band. A small fraction could then be detectable with current high- or very-high-energy (VHE) γ -ray telescopes [6, 7, 8, 9] such as *Fermi*-LAT (20 MeV – 300 GeV) [10] and imaging air Cherenkov telescopes (IACTs; $E \gtrsim 100$ GeV) [11].

This article summarizes the main results of a study on the detectability of DM subhalos with *Fermi*-LAT, their properties, and the investigation of the most promising object from first searches for subhalo candidates in the first *Fermi*-LAT point-source catalog (1FGL), 1FGL J0030.7+0724. For details and further explanation the reader is referred to Zechlin et al., 2011 [12].

2. Gamma rays from DM subhalos

The total rate of photons with energy E in the interval $[E_1; E_2]$, originating from self-annihilating DM in a DM subhalo, is

$$\mathcal{L} = \frac{\langle \sigma v \rangle_{\text{eff}} N_{\gamma}}{2m_{\chi}^2} \int dV \rho^2(r), \quad N_{\gamma} = \int_{E_1/m_{\chi}}^{E_2/m_{\chi}} dx \frac{dN_{\gamma}}{dx}, \quad (1)$$

where $\langle \sigma v \rangle_{\text{eff}}$ is the thermally-averaged annihilation cross section times the relative velocity, m_{χ} the WIMP

mass, and dN_γ/dx , $x \equiv E/m_\chi$, denotes the differential spectrum of photons per annihilation [13]. The produced photon flux is $\phi = \mathcal{L}/(4\pi D^2)$, assuming $r_s \ll D$ (see below). Consistent with numerical simulations, the density profile of DM subhalos is taken to follow a Navarro-Frenk-White (NFW) profile [14], scaled to the characteristic inner radius r_s and characteristic inner density ρ_s . For subhalos, where (e.g., tidal) disturbances caused by their formation history are negligible, the profile parameters are related by the virial halo mass M_{vir} . The quantity M_{vir} is given by the mass inside the sphere of radius R_{vir} , which encloses a mean density of Δ_c times the critical density of the Universe ρ_{crit} at the considered redshift z [14], $M_{\text{vir}} := 4\pi/3 \Delta_c \rho_{\text{crit}} R_{\text{vir}}^3$. The virial overdensity at $z = 0$ is $\Delta_c \approx 100$ [15]. Integrating the NFW profile, the subhalo mass M is given by $M = 4\pi \rho_s r_s^3 f(c)$, where $f(c) \equiv \ln(1+c) - c/(1+c)$ and c denotes the concentration parameter of the subhalo. For non-disturbed halos, the concentration is defined by $c_{\text{vir}} \equiv R_{\text{vir}}/r_s$, depending on the subhalo mass and redshift. In the following, we use the low-mass extrapolation of a toy model for c_{vir} [16], based on [17]. Corrected by a factor depending on the galactocentric distance, effects of subhalo formation processes will be included. In this model, henceforth *subhalo model* (SHM), the concentration increases with decreasing galactocentric distance, as indicated by numerical simulations [7]. Intrinsic to the stochastic process of halo formation, the concentration of individual subhalos scatters around the median, see [17, 18]. A general study of the concentration-model dependence and further details are given in [12].

Given the relations above, Eq. 1 simplifies to

$$\mathcal{L} = \frac{\langle \sigma v \rangle_{\text{eff}} N_\gamma \Delta_c \rho_{\text{crit}}}{18 m_\chi^2} \frac{M c_{\text{vir}}^3}{f(c_{\text{vir}})^2}. \quad (2)$$

Conveniently, $\langle \sigma v \rangle_{\text{eff}}$ is normalized to $\langle \sigma v \rangle_0 = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$, which coincides with the correct relic density. A higher annihilation rate, a so-called boost factor $\langle \sigma v \rangle_{\text{eff}}/\langle \sigma v \rangle_0$, could in general be related to sub-substructures or the particular particle physics framework.

3. Fermi-LAT sources as DM subhalos

Based on the observational quantities flux and angular extent, candidate sources for DM subhalos will be selected. With Eq. 2, the effective self-annihilation cross section $\langle \sigma v \rangle_{\text{eff}}$ required for a given flux ϕ and intrinsic source extent θ_s is determined with $\mathcal{L} = 4\pi D^2 \phi$, where θ_s constrains the distance D to the subhalo. The intrinsic extent of a subhalo is traced by the characteristic profile radius r_s , since 87.5% of the total γ -ray luminosity is produced within r_s .

Hence, $D \approx r_s/\theta_s$, where θ_s denotes the angle corresponding to r_s . About 68% of the γ -ray luminosity is emitted within $\theta_{68} \simeq 0.46 \theta_s$. The relations below are given with respect to θ_s , but can easily be adapted for θ_{68} , which represents the extent for comparison with observational data. With the WIMP model, $\langle \sigma v \rangle_{\text{eff}}$ is fully determined by the subhalo mass and the observed flux and extent:

$$\langle \sigma v \rangle_{\text{eff}} = 96 \pi^{\frac{1}{3}} \frac{m_\chi^2}{N_\gamma} \left(\frac{3}{4 \Delta_c \rho_{\text{crit}}} \right)^{5/3} \frac{\phi}{\theta_s^2} \frac{M^{-1/3} f(c_{\text{vir}})^2}{c_{\text{vir}}^5}. \quad (3)$$

For heavy WIMPs, a detection of DM subhalos is favored in the high-energy band of *Fermi*-LAT (10 – 100 GeV), due to improving sensitivity [10] and the energy spectrum of DM annihilation. As will be demonstrated later, a fiducial subhalo candidate source is characterized by faintness and a moderate angular extent. Therefore, the flux of the fiducial source is chosen to be at the level of detection sensitivity (one year), which has been accurately studied in [12]: $\phi^{\text{fid}}(10 - 100 \text{ GeV}) = 1.6 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ for $\theta_s^{\text{fid}} = 1^\circ$, corresponding to $\theta_{68}^{\text{fid}} \approx 0.5^\circ$; the Galactic position has been chosen to match 1FGL J0030.7+0724.

For WIMPs of $m_\chi = 150 \text{ GeV}$ fully annihilating to $\tau^+ \tau^-$, the effective boost factors $\langle \sigma v \rangle_{\text{eff}}/\langle \sigma v \rangle_0$ required to generate the emission ϕ^{fid} of the fiducial source by DM annihilation are depicted in Fig. 1. Within the halo-to-halo scatter of the concentration, the required boost spans about one order of magnitude. Minimal boost is required for massive subhalos between 10^6 and $10^7 M_\odot$. In Fig. 1, the necessary effective annihilation cross section is compared with current observational limits on $\langle \sigma v \rangle_{\text{eff}}/\langle \sigma v \rangle_0$ [19, 20]. The Figure shows that, within the scatter, the boost factor needed to explain γ -ray sources such as the fiducial with massive DM subhalos ($\sim 10^5 - 10^8 M_\odot$) is consistent with observational constraints. These subhalos are in corresponding distances from 0.5 to 10 kpc. Further reduction of the boost could be accomplished by additional sub-substructure (factor of 2-3, [21]). For the considered WIMP model, this leads to a required boost of order unity within the scatter.

For this WIMP model and current observational constraints on $\langle \sigma v \rangle_{\text{eff}}$, on average 0.2 subhalos between 10^5 and $10^8 M_\odot$ are expected for detection with *Fermi*-LAT in one year, see [12]. Given the Poisson distribution of the average, up to one massive subhalo is expected in the one-year data set.

4. Searches for DM subhalos in the 1FGL

As shown above, DM subhalos would appear as faint, non-variable, and moderately extended sources without astrophysical counterparts. First candidates have been searched for in the 11-months point-source catalog of *Fermi*-LAT (1FGL, 100 MeV - 100 GeV,

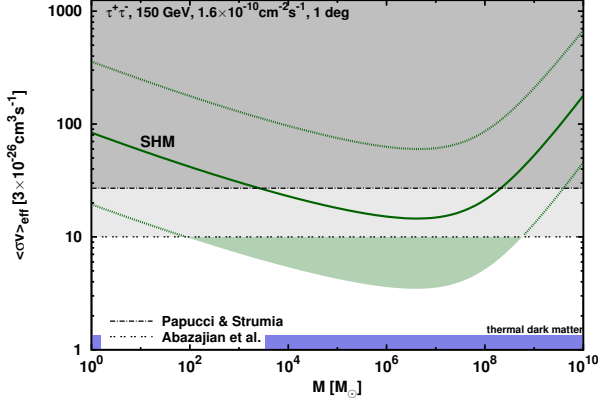


Figure 1: Boost factor $\langle\sigma v\rangle_{\text{eff}}$ required for the fiducial *Fermi*-LAT source to originate from a DM subhalo of mass M . The solid green line indicates the prediction of the average SHM model, while its scatter is depicted by the dotted green lines (and the green-shaded area). Current observational constraints on $\langle\sigma v\rangle_{\text{eff}}$ are shown by the light grey- and grey-shaded area.

[22]), listing 1451 γ -ray sources together with flux, position, significance of variability, and spectral curvature. Among the sources, 630 objects are not confidently associated with known sources at other wavelengths.

To select possible subhalo candidates, the sample of unassociated sources has been scanned for non-variable sources detected between 10 and 100 GeV. A high-energy detection assures subhalo candidates driven by heavy WIMPs and furthermore avoids confusion with high-energy pulsars [23]. The position in the Galaxy has been constrained to galactic latitudes $|b| \geq 20^\circ$, eliminating confusion with Galactic sources.

Twelve unassociated sources pass these cuts. Apart from one, the sample consists of sources at the faint end of the entire 1FGL sample. A further discussion of these objects is presented in [12]. According to the 1FGL catalog, the counterpart search has been extended to a wider choice of astronomical catalogs. Given the twelve candidates, the most promising has been selected, governed by lacking association, faintness, and spectral shape, namely 1FGL J0030.7+0724.

Both the high-energy flux of 1FGL J0030.7+0724, $\phi_p(10 - 100 \text{ GeV}) = (1.5 \pm 0.7) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$, as well as the spectral index, $\Gamma = 1.7 \pm 0.4$, are well compatible with a self-annihilating DM origin. Note that the source has only been significantly detected between 10 and 100 GeV. Within the positional uncertainty of the γ -ray signal (at 95% confidence), 1FGL J0030.7+0724 has no convincing multi-wavelength counterpart. Furthermore, X-ray observations with ROSAT [24] constrain the energy-flux of a possible X-ray counterpart to $\lesssim 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ [25].

4.1. *Fermi*-LAT data

For further investigation of possible counterparts, temporal variability, and the angular extent of 1FGL J0030.7+0724, updated results based on the 24-months public archival data set of *Fermi*-LAT between 10 and 100 GeV have been derived. The point-source analysis has been performed with the *Fermi Science Tools* v9r18p6 [26], using recommended options and the instrument-response functions *P6_V3_DIFFUSE* [27]. Details are given in [12].

Within a radius of 0.5° around the nominal source position, six photons (one class 3 event, five class 4 events) between 10 and 100 GeV have been detected after 24 months. With respect to the signal, the influence of the Galactic foreground as well as the extragalactic background at the source position is negligible. The integrated flux between 10 and 100 GeV, reconstructed with the point-source analysis, is $\phi_p(10 - 100 \text{ GeV}) = (0.9 \pm 0.4) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$. The significance of the signal in this energy-bin is about 6.6 Gaussian standard deviations.

The variability of 1FGL J0030.7+0724 has been tested for, analyzing the temporal photon distribution for compatibility with a constant flux with an unbinned Kolmogorov-Smirnov test. The test confirms the null-hypothesis of a steady flux with a probability of about 0.5. Given the positional distribution of the signal photons, the (intrinsic) spatial extent has been tested with a likelihood-ratio test, comparing the null-hypothesis of a point-source with the assumption of the intensity distributed following the line-of-sight integral of the squared NFW profile. The data favors a moderate extent $\theta_s = 0.14^{+0.20}_{-0.12} \text{ deg}$, which is, however, not significantly different from a point-source hypothesis. The upper limit is $\theta_s \leq 0.72 \text{ deg}$ at 95% confidence level.

4.2. *Swift*-XRT data

New observations of the field with the X-ray telescope (XRT, 0.2-10 keV) onboard the *Swift* satellite [28] with a total effective exposure of 10.1 ks led to the discovery of seven new X-ray sources. The (unabsorbed) energy fluxes of the discovered sources range from $\sim 2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ to $2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ between 0.2 and 2 keV. See [12] for further details.

5. Discussion

5.1. 1FGL J0030.7+0724 as AGN

Within the updated positional information on 1FGL J0030.7+0724 (see Sect. 4.1), the radio source NVSS J003119+072456 ($f_{1.4 \text{ GHz}} = (11.6 \pm 0.6) \text{ mJy}$) provides a viable counterpart. The radio

source positionally coincides with the newly discovered hard X-ray source SWIFT J003119.8+072454 ($\Gamma = 1.6 \pm 0.3$), energy flux $\sim 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ between 0.2 and 2 keV, and the optical counterpart SDSS J003119.71+072453.5 ($m(r) = 17.4^m$). Normalized to the radio flux, the average spectral energy distribution of a high-energy-peaked blazar (HBL, see [29]) fits the data, assuming standard temporal variability of the source. Reinforcing, the HBL scenario is favored by the spectral indices of the X- and γ -ray signal.

The optical counterpart appears point-like with $m(R) = 18.6^m$ (the SDSS source coincides with USNO 0974-0005617). Under the assumption of an elliptical host galaxy with $M_R = -23.1^m$, typical for blazars [30], the corresponding distance modulus implies a redshift of $z = 0.39 \pm 0.03$ (K-correction).

5.2. 1FGL J0030.7+0724 as DM subhalo

Given the absence of clear indication for variability, a DM subhalo origin of 1FGL J0030.7+0724 remains plausible. The flux^[31] and the upper limits on the angular extent provided in Sect. 4.1 are consistent with a subhalo of mass between 10^6 and $10^8 M_\odot$. Assuming a mass of $10^6 M_\odot$, the distance would be $2.4^{+1.0}_{-0.7} \text{ kpc}$ given the scatter of the concentration model, see Sects. 2 and 3. In case of a WIMP of 150 GeV annihilating to $\tau^+\tau^-$, the required minimal boost is 3 for a high-concentrated subhalo with a corresponding distance of 1.7 kpc, and 13 for an average-concentrated subhalo with a corresponding distance of 2.4 kpc. An even lower boost may be required, if the subhalo contains sub-substructures or exhibits a cuspid profile.

6. Summary and Outlook

We have presented a state-of-the-art investigation on the detectability of DM subhalos with the *Fermi*-LAT. Concluding, one massive DM subhalo will probably appear in the first catalog. First searches have indeed revealed twelve possible candidates, where the most promising, 1FGL J0030.7+0724, has been studied in detail. A detection of temporal variability and improved astrometry would clarify the physical origin of this object.

The accompanying paper Zechlin et al., 2011 [12] will contain additional details. The recent release of the second *Fermi*-LAT catalog, 2FGL, allows a deeper search for subhalo candidates, which will be presented in a future work. Note that related work is presented in [32] and [33].

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